Figure IV-2-15. Southeast coast of Hawaii, near Kalpana. Rugged cliffs are built up of many lava flows. Small pocket beaches form between headlands when the cliffs are undermined and loose sediment accumulates

Volcanoes seem a remote hazard to most people, but the danger is imminent and real to those who live in certain parts of the earth, especially along the boundaries of the earth's tectonic plates. Fortunately, fewer than 100 people have been killed by eruptions in Hawaii, where the volcanism is less explosive (Tilling, Heliker, and Wright 1987).

(2) Earthquakes and tsunamis.

(a) *Tsunamis* are waves created by ocean-bottom earthquakes, submarine landslides, and volcanic explosions. These long-period waves can travel across entire oceans at speeds exceeding 800 km/hr, causing extensive damage to coastal areas. The cataclysmic explosion of Krakatau on August 27, 1883, generated waves 30 m high that swept across the Sunda Strait, killing 36,000 coastal villagers on Java and Sumatra. One explosion produced one of the loudest noises in history, which was heard at a distance of 4800 km. The Hawaiian islands are particularly vulnerable to tsunamis caused by disturbances around the Pacific rim. The tsunami of April 1, 1946, generated towering walls of water that swept inland, damaging many coastal structures on the islands. In areas, the water rose to 16 m above the normal sea level. Photographs of the waves and the resulting damage are printed in Shepard and Wanless (1971) (Francis Shepard was living on Oahu at the time and vividly describes how the waves smashed his bungalow, forcing him and his wife to flee for their lives). On July 17, 1998, a wall of water 7 m high hit the northwest coast of Papua, New Guinea without warning, following a 7.0 magnitude earthquake about 30 km off the coast in the Pacific Ocean. Some 6,000 villagers perished in this tragedy.

Figure IV-2-16. Laupahoehoe Harbor, Island of Hawaii, Hawaii. Found on the steep and rugged northeast coast of Hawaii, this harbor provides the only access to the fertile Hamakua coast fishing grounds. This is a hostile environment, as shown by the basalt boulders tossed onto the boat ramp by storm waves

(b) Clearly, there is little that can be done to protect against the random and unpredictable tsunamis. A warning network has been established to notify people around the Pacific of earthquakes and the possibility that destructive waves may follow. Coastal residents are urged to heed these warnings!

(3) Ash and fluvial sediment. When Mount St. Helens exploded on May 18, 1980, 390 m of the top of the mountain was blown off, spewing a cloud of dust and ash high into the stratosphere. From its north flank, an avalanche of hot debris and scalding gasses created immense mudflows, burying the upper 24 km of the North Toutle valley to a depth of 50 m. Lahars, formed from dewatering of the debris avalanche, blocked the shipping channel of the Columbia River. This created an enormous dredging task for the U.S. Army Corps of Engineers, and ultimately much of the dredged material had to be disposed at sea. Dredging related to the explosion continues 18 years after the eruption, as material continues to move downstream from mountain watersheds.

(4) Explosive destruction. Communities close to volcanoes may be destroyed by the explosion and the inhabitants killed by poisonous gasses and superheated steam.

(a) The coastal example frequently cited is the destruction of St. Pierre on Martinique by the violent explosion of Montagne Pelée on May 8, 1902. A glowing cloud overran St. Pierre and spread fan-like over the harbor. Practically instantly, the population of more than 30,000 was smothered with toxic gas and incinerated (Bullard 1962).

(b) The cloud that destroyed St. Pierre consisted of superheated steam filled with even hotter dust particles, traveling more than 160 km/hr. The term *nuée ardente* is now used to describe this type of swiftly flowing, gaseous, dense, incandescent emulsion. It is also used as a synonym for the Peléan type of eruption.

IV-2-8. Sea Cliffs - Diastrophic, Erosional, and Volcanic

a. Sea cliffs are the most spectacular geomorphic features found along the world's coastlines. This section concentrates on bedrock cliffs, with *bedrock* defined as "the solid rock that underlies gravel, soil, or other superficial material" (Bates and Jackson 1984). Bedrock cliffs are found along most of the U.S. and Canadian Pacific coast, in Hawaii, along the Great Lakes shores, and in Maine. South of Maine along the Atlantic coast, cliffs are rare except for some examples in New Hampshire, Massachusetts, and Rhode Island. The eastern end of Long Island, Montauk Point, consists of rapidly eroding till bluffs (Figure IV-2-9). Cliffs constitute portions of the coastlines of Spain, Italy, Greece, Turkey, Iceland, and the South American nations facing the Pacific Ocean. Shorelines with cliffs may be both emergent or submergent. For more information, Trenhaile's (1987) *The Geomorphology of Rock Coasts* presents a comprehensive and global review of cliffs, shore platforms, and erosion and weathering processes.

b. Bedrock cliffs are composed of all three major rock types: igneous, sedimentary, and metamorphic.

(1) ***Intrusive igneous rock***, such as granite, cools and solidifies beneath the earth's surface, while *extrusive igneous rock*, such as basalt, is formed by lava above ground (it may erupt underwater or on land). Usually, igneous rocks are highly resistant; however, two properties affect their susceptibility to weathering and erosion (de Blij and Muller 1993):

(a) *Jointing* is the tendency of rocks to develop parallel sets of fractures without obvious external movement like faulting.

(b) *Exfoliation*, caused by the release of confining pressure, is a type of jointing which occurs in concentric shells around a rock mass.

(2) ***Sedimentary rock*** results from the deposition and lithification (compaction and cementation) of mineral grains derived from other rocks (de Blij and Muller 1993). This category also includes rock created by precipitation (usually limestone).

(a) The particles (clasts) that make up *clastic sedimentary rock* can range in size from windblown dust to waterborne cobbles and boulders. The vast majority of sedimentary rocks are clastic. Common examples include sandstone, composed of lithified sand (usually consisting mostly of quartz), and shale, made from compacted mud (clay minerals). Many cliffs along the south shore of Lake Erie are shale.

(b) *Nonclastic sedimentary rocks* are formed by precipitation of chemical elements from solution in marine and freshwater bodies because of evaporation and other physical and biological processes. The most common nonclastic rock is limestone, composed of calcium carbonate ($CaCO_3$) precipitated from seawater by marine organisms (and sometimes also incorporating marine shell fragments). Many of the Mediterranean cliffs are limestone and are very vulnerable to dissolution.

(3) ***Metamorphic rocks*** are preexisting rocks changed by heat and pressure during burial or by contact with hot rock masses. Common examples include:

(a) *Quartzite*, a very hard, weathering-resistant rock, formed from quartz grains and silica cement.

(b) *Marble*, a fine-grained, usually light-colored rock formed from limestone.

(c) *Slate*, a rock that breaks along parallel planes, metamorphosed from shale.

c. Sea cliffs are formed by three general processes:

(1) Volcanic eruptions and uplift caused by local volcanism (discussed in paragraph IV-2-7).

(2) Diastrophic activity that produces vertical movement of blocks of the crust.

(3) Erosional shorelines - partial drowning of steep slopes in hilly and mountainous terrain and resulting erosion and removal of sediment.

d. Sea cliffs, often found on tectonically active coasts, may be created by two mechanisms. First, if a block of the coast drops, a newly exposed fault plane may be exposed to the sea. The opposite process may occur: a block may be uplifted along a fault plane, exposing a formerly exposed portion of the shoreface to marine erosion. Older cliffs may be raised above sea level and be temporarily protected from further erosion. Earlier shorelines, sometimes tens of meters above the present sea level, are marked by notches or wave-cut platforms (sometimes termed uplifted marine terraces) (Figure IV-2-17). Terraces marking the highstand of eustatic (absolute) sea level have been traced around the world. Deep water is often found immediately offshore of faulted coasts. Cliffs that extend steeply into deep water are known as plunging cliffs.

e. *Erosional coasts* may be straight or may be irregular, with deeply indented bays. The way the shore reacts to inundation and subsequent marine erosion depends on both the wave climate and the rock type.

(1) Wave-straightened coasts. Cliffs are often found along shores where wave erosion rather than deposition is the dominant coastal process. Exposed bedrock, high relief, steep slopes, and deep water are typical features of erosional shorelines (de Blij and Muller 1993). When islands are present, they are likely to be remnants of the retreating coast rather than sandy accumulations being deposited in shallow water. The sequence of events that create a straightened coast are illustrated in Figure IV-2-18. The original coastline includes headlands and embayments (a). As waves attack the shore, the headlands are eroded, producing steep sea cliffs (b). The waves vigorously attack the portion of the cliff near sea level, where joints, fissures, and softer strata are especially vulnerable. The cliffs are undermined and caves are formed. Pocket beaches may accumulate between headlands from sediment carried by longshore currents. Especially durable pinnacles of rock may survive offshore as stacks or arches. Over time, the coast is straightened as the headlands are eroded back (c).

(a) Beaches. Beaches may form at the base of cliffs if the rubble that has fallen from the cliff face (known as talus) is unconsolidated or friable and breaks down rapidly under wave attack (Figures IV-2-9 and IV-2-15). If the rock debris is durable, it may serve to armor the shore, protecting it from further wave attack except during the most severe storms.

(b) Wave-cut platforms. At the base of cliffs that have been progressively cut back by waves, near-horizontal platforms may form just below sea level. These rocky platforms may be of substantial width, depending on lithology and the time that sea level has been at that height (Figure IV-2-17). The platforms may be clean or may be covered with rubble fallen from the adjacent cliffs.

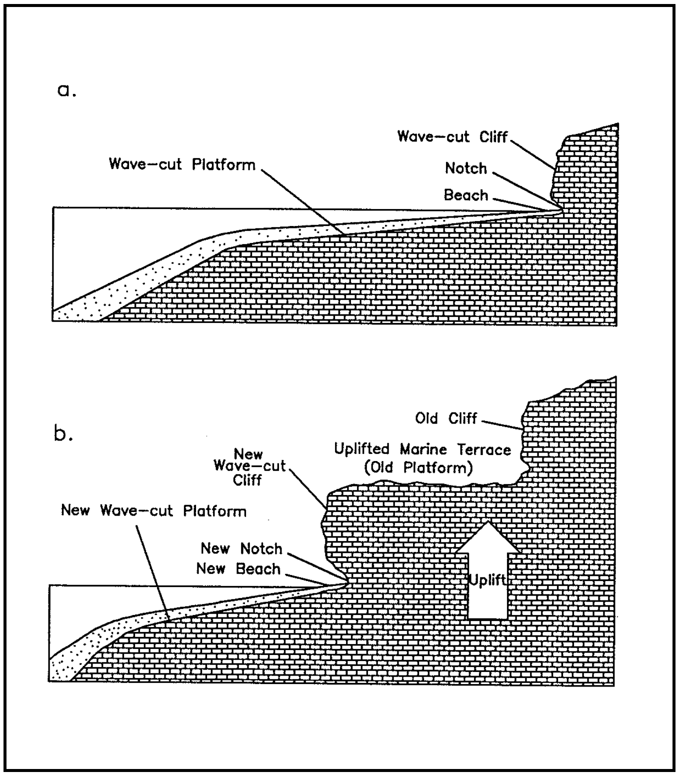

Figure IV-2-17. Wave-cut platform exposed by tectonic uplift. Sediment that accumulated on the platform may temporarily protect the cliff from further erosion

(2) Creation of irregular shorelines. In some mountainous terrains, rising sea level results in deeply incised coastlines. This process is illustrated in Figure IV-2-19. As the sea rises, a river valley is inundated. Once exposed to the sea, the new shoreline is subject to dissolution and biological attack. In southern France, Italy, Greece, and Turkey, thousands of deep embayments are found in the coastal limestone hills. The fact that the wave climate in the Mediterranean is relatively calm (compared with the open oceans) suggests that erosional processes other than wave attack have been instrumental in creating these steep, indented shores. An irregular shore may also be formed when differing rock types outcrop at the coast. Massive rocks, especially igneous and metamorphic ones, withstand erosion better than most sedimentary rocks, which are usually friable and contain bedding planes and fractures. The Pacific coast of Washington off the Olympic Peninsula is irregular because of the complex geology and variety of exposed rock formations (Figure IV-2-20).

e. Marine cliffs are degraded by many physical and biological factors.

(1) Wave attack is most likely the primary mechanism that causes cliffs to erode (Komar 1976). The hydraulic pressure exerted by wave impact reaches values sufficient to fracture the rock. Sand and rock fragments hurled at the cliff by waves grind away at the surface. Komar (1976) states that wave erosion occurs chiefly during storms, but admits that little quantitative research has been conducted. Once a cliff has been undercut at its base, the overlying rock, left unsupported, may collapse and slide down to the shoreline (Figures III-5-21, IV-2-21, and IV-2-22). Temporarily, the talus protects the cliff, but over time the rubble is reduced and carried away, leaving the fresh cliff face exposed to renewed wave attack.

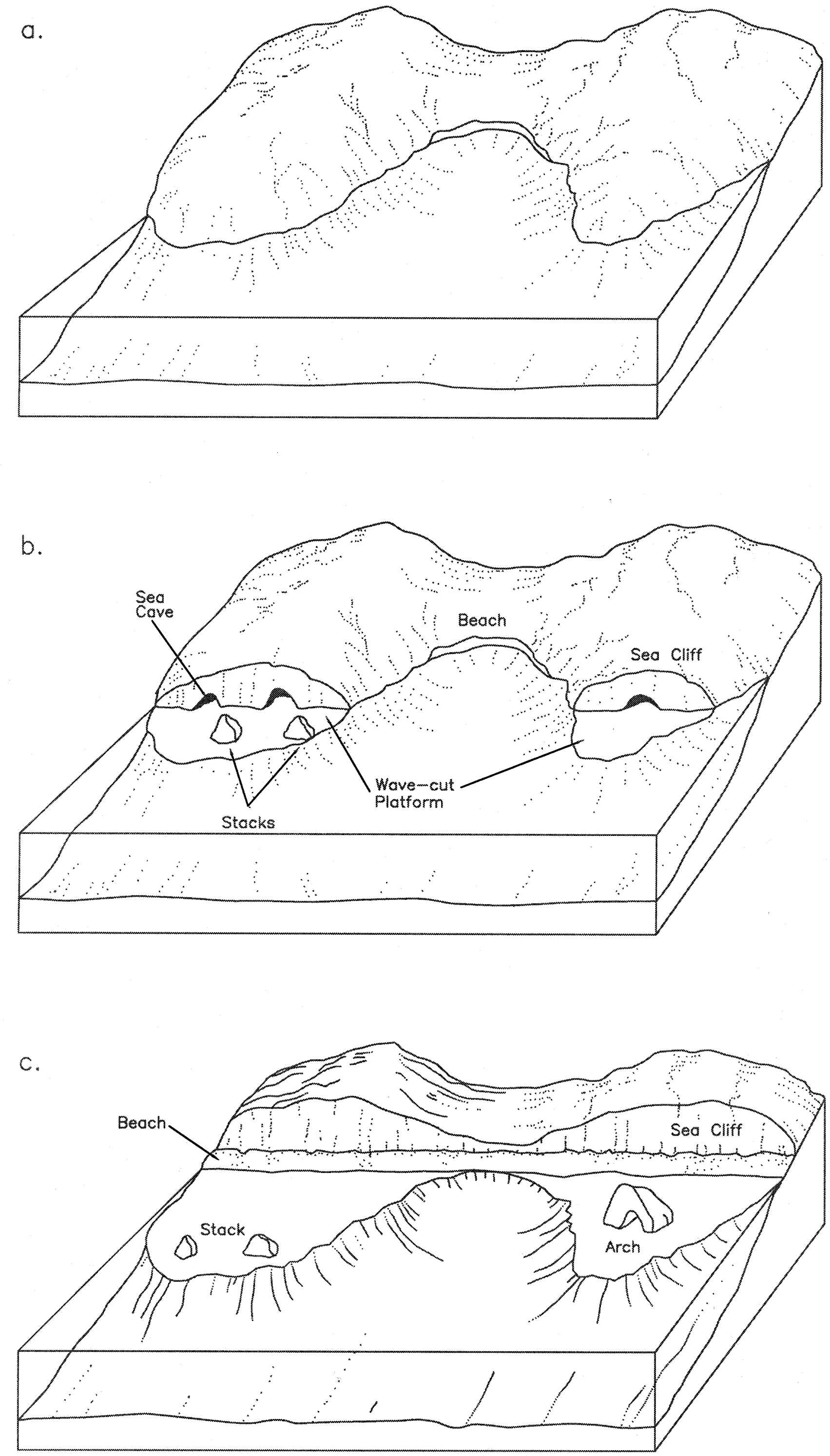

Figure IV-2-18. Wave erosion of an indented coastline produces a straightened, cliff-bound coast. Wave-cut platforms and isolated stacks and arches may remain offshore. Many such features are found along the Washington, Oregon, and California coast (adapted from de Blij and Muller (1993))

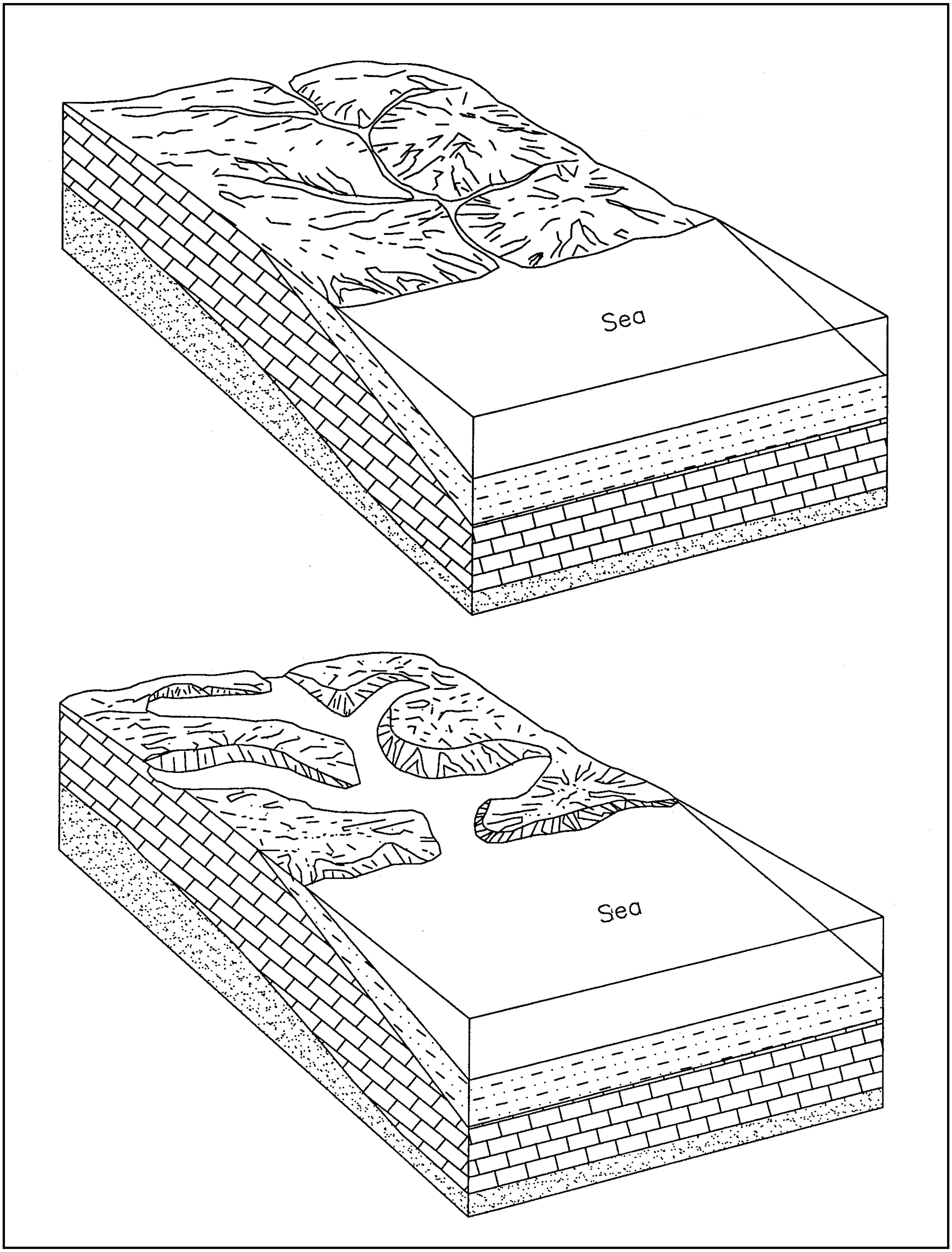

Figure IV-2-19. Inundation of a mountainous area by rising sea level or land subsidence produces a deeply indented shoreline

Figure IV-2-20. Pacific Ocean coast of Olympic Peninsula, Washington, near Jefferson Cove (September 1971). Rugged shore consists of resistant rock headlands with pocket beaches. Much of the beach sediment is cobble and coarse clasts derived from the adjacent cliffs. The beaches are often covered with logs and driftwood

(2) In addition to waves, weathering processes weaken and crumble sea cliffs. Ice wedging in cold climates progressively weakens the rock. Plant roots grow and expand in cracks. Lichens secrete acids that etch the rock surface. Groundwater can lubricate impermeable rock surfaces, upon which large masses of overlying rock can slip. This process is responsible for large slumps in the shale bluffs in Lakes Erie and Ontario (Figure III-5-21).

(3) Mollusks and burrowing animals can weaken otherwise resistant massive rocks. Komar (1976) lists burrowing mollusks such as *Pholadidae* and *Lithophaga*, and periwinkles, worms, barnacles, sponges, and sea urchins as having been observed to erode rock. Boring algae can also weaken rock (Figure IV-2-23).

(4) Under normal circumstances, surface seawater is saturated with calcium carbonate ($CaCO_3$), therefore minimizing dissolution of limestone or $CaCO_3$-cemented sediments. Marine organisms can locally increase the acidity of the water in high-tide rock basins and other protected locations. Small pockets found